

THE UNUSUAL SMOOTHNESS OF THE EXTRAGALACTIC UNRESOLVED RADIO BACKGROUND

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ABSTRACT

If the radio background is coming from cosmological sources, there should be some amount of clustering due to the large scale structure in the universe. Simple models for the expected clustering combined with the recent measurement by ARCADE-2 of the mean extragalactic temperature lead to predicted clustering levels that are substantially above upper limits from searches for anisotropy on arcminute scales using ATCA and the VLA. The rms temperature variations in the cosmic radio background appear to be more than a factor of 10 smaller (in temperature) than the fluctuations in the cosmic infrared background. It is therefore extremely unlikely that this background comes from galaxies, galaxy clusters, or any sources that trace dark matter halos at $z \lesssim 5$, unless typical sources are smooth on arcminute scales, requiring typical sizes of several Mpc.

1. INTRODUCTION

Recent observations of the extragalactic radio background (Fixsen et al. 2011) have provided a precise measurement of the temperature of the extragalactic sky as a function of frequency at GHz frequencies. The measured temperature is roughly an order of magnitude larger than expectations based on extrapolations of faint source counts (Gervasi et al. 2008). This relatively high extragalactic radio temperature has proven difficult to understand theoretically (Seiffert et al. 2011; Singal et al. 2010), including attempts to link the radio background to dark matter annihilations (Fornengo et al. 2011; Hooper et al. 2012).

Given that the mean temperature is difficult to understand, a natural next question is whether the variance can be understood, i.e., the clustering of the radio background. Clustering of the cosmic infrared background (CIB) has been recently measured by many experiments (Viero et al. 2009; Hall et al. 2010; Planck Collaboration et al. 2011), and these measurements have provided new insights into the sources that contribute to the CIB (Pénin et al. 2012). Clustering measurements of the cosmic radio background (hereafter, CRB) can provide similar information about the sources that contribute.

In this short letter we first review the observed upper limits on clustering at GHz frequencies, then calculate the expected levels of clustering in some simple scenarios. We will show that the expected level of clustering (rms) is substantially larger than observed upper limits, requiring either that the emission comes from high redshifts ($z \gtrsim 5$), or is coming from sources that are extremely smooth on arcminute scales (typical source sizes of a few Mpc or larger).

2. OBSERVED UPPER LIMITS ON CLUSTERING

To date, there have been measurements of the angular power spectrum of resolved sources (Blake et al. 2004), but there exist only upper limits on fluctuations of the unresolved radio background.

Searches for cosmic microwave background (CMB) anisotropies at low frequencies provide the strongest constraints on clustering of the radio background. Searches have been done for anisotropies using the Very Large Ar-

ray (VLA) at frequencies of 4.86 GHz (Fomalont et al. 1988) and 8.4 GHz (Partridge et al. 1997), and using the Australia Telescope Compact Array (ATCA) at 8.7 GHz (Subrahmanyan et al. 2000). No anisotropy was detected in any of these searches, yielding only upper limits, shown in Table 1.

These limits on CMB fluctuations can also be used as limits on CRB clustering. To convert to fractional variations in the radio background, we simply need to replace the normalization by T_{cmb} with the extragalactic radio background temperature as a function of frequency ν .

The ARCADE-2 experiment recently reported measurements of the radio background at frequencies of 3, 8 and 10 GHz (Fixsen et al. 2011) and combined these data with measurements in the literature to determine the extragalactic radio temperature from 22 MHz to 10 GHz:

$$T_{arcade} = 1.26 \pm 0.09 \text{K} \left(\frac{\nu}{\text{GHz}} \right)^{-2.6 \pm 0.04}. \quad (1)$$

Using extrapolations of known source counts (Gervasi et al. 2008), the expected temperature of the radio sky is

$$T_{counts} = 0.23 \text{K} \left(\frac{\nu}{\text{GHz}} \right)^{-2.7}. \quad (2)$$

The residual background from unresolved sources is defined to be $T_{excess} = T_{arcade} - T_{counts}$. CMB anisotropy searches generally either remove or avoid bright point sources; for these purposes we assume that all contributions from known sources have been removed, which will in practice be a slight overestimate of source removal efficiency. This will in turn lead to overly conservative upper limits on the clustering of the CRB. Upper limits on the CRB (using T_{excess}) are shown in Table 1 for the various experiments. The most stringent constraints are from the 4.9 GHz VLA experiment and ATCA at 8.7 GHz, requiring rms fluctuations in the CRB to be below 1% on arcminute scales.

As a point of comparison, the recent measurements of clustering of the cosmic infrared background (CIB) using the Planck experiment find that $\Delta T/T_{CIB} \sim 0.1\text{--}0.15$ at mm-wave frequencies (Planck Collaboration et al. 2011).

Frequency	$\theta(^{\circ})$	95% confidence upper limits		
		dT/T_{cmb}	dT/T_{arcade}	dT/T_{excess}
4.86 GHz Fomalont et al (1988)	12	8.5×10^{-4}	0.11	0.13
	18	1.2×10^{-4}	0.016	0.019
	30	8×10^{-5}	0.011	0.013
	60	6×10^{-5}	0.008	0.009
8.4 GHz Partridge et al (1997)	6	1.3×10^{-4}	0.070	0.082
	10	7.9×10^{-5}	0.043	0.051
	18	4.8×10^{-5}	0.026	0.031
	30	3.5×10^{-5}	0.019	0.023
	60	2.0×10^{-5}	0.011	0.013
	80	2.1×10^{-5}	0.011	0.014
8.7 GHz Subrahmanyan et al (2000)	120	1.4×10^{-5}	0.0084	0.0099

TABLE 1

UPPER LIMITS (95% CONFIDENCE) ON THE FRACTIONAL RADIO BACKGROUND ANISOTROPY OBTAINED FROM CMB ANISOTROPY LIMITS (COLUMN 3) USING THE TEMPERATURE MEASURED BY THE ARCADE-2 EXPERIMENT (COLUMN 4) AND CORRECTED FOR KNOWN SOURCE POPULATIONS (COLUMN 5).

Whatever is contributing to the extragalactic radio background must have rms fluctuations that are more than an order of magnitude smaller than the sources that contribute to the CIB.

3. EXPECTED CLUSTERING OF THE RADIO BACKGROUND

Calculating the expected clustering of the CRB is difficult to do at high precision, since the redshift distribution of the sources is not well known and it is not known how radio sources trace dark matter halos. However, it is possible to roughly estimate the expected amount of clustering for different assumptions about the typical masses and redshifts for the radio sources that could contribute to the radio background.

We adopt a simple linear bias model (Kaiser 1984), where it is assumed that fluctuations in the number density of galaxies are proportional to the fluctuations in the matter density $\Delta n/n = b\Delta\rho/\rho$. The constant of proportionality depends on the mass and redshift of the dark matter halos that host the sources of interest. For rare objects, one expects b to be substantially greater than 1, while it is possible for b to be less than 1 for very low mass objects. However, it is not expected that $b \lesssim 0.5$ for any population that traces dark matter halos (Mo & White 1996; Seljak & Warren 2004). For simplicity, in what follows we assume $b = 1$ at all redshifts for the sources that make up the radio background.

To calculate the expected CRB fluctuations, we follow the procedure for calculating CIB fluctuations laid out in Haiman & Knox (2000). The distribution in redshifts that contribute to the extragalactic radio background is not well known. If we write the fraction of the radio background contributed by a distance $d\chi$ in comoving distance as $df/d\chi$, then the angular power spectrum of temperature fluctuations as a function of multipole number ℓ can be obtained using the Limber approximation (Kaiser 1992) as

$$C_\ell(\ell) = \int d\chi \frac{1}{\chi^2} \left(\frac{df}{d\chi} \right)^2 P\left(\frac{\ell}{\chi}, \chi\right), \quad (3)$$

where $P(k, \chi)$ is the matter power spectrum at wavenumber k at comoving distance χ . For these calculations we

use the linear power spectrum, ignoring the increased power expected in the presence of non-linear evolution. On the scales of interest, non-linearity could increase the predicted power by large amounts; for this work we are most interested in lower limits to the predicted power, given the remarkable apparent smoothness of the radio sky.

In the absence of a specific model for the radio background, we investigate the simplest $df/d\chi$: a top hat function in comoving distance, where it is assumed that the cosmic radio background is generated uniformly in comoving distance between some redshifts z_{min} and z_{max} . Predicted angular power spectra are shown in Figure 1, along with the limits from Table 1. To convert angle to multipole for the observed upper limits, we use $\ell \sim 2.35/\theta$, where θ is the FWHM of the beam in radians. The observed upper limits are in clear tension with theoretical expectations for a normal population of galaxies.

As a cross-check on this simple model, we can use observed clustering. For the CIB, the fractional fluctuations found by Planck at 845 GHz are of order 10-15% (Planck Collaboration et al. 2011), consistent with a population of galaxies with bias factors around two and/or a small amount of non-linear evolution. Using resolved galaxies in the NVSS survey, the fluctuations in radio galaxy number density on degree scales were found to be of order 3.5% at $l \sim 100$ (Blake et al. 2004), consistent with the predictions in Figure 1, especially within the large uncertainties of redshift distributions and unknown bias factors.

To get extremely low clustering amplitudes, it is required to have a broad range in redshifts contributing (to have more averaging of fluctuations along the line of sight) and/or to have contributions from higher z (where the matter power spectrum amplitude is lower due to the growth of structure).

Another way to suppress the small-scale clustering is to have the sources be intrinsically large, with very little structure on the arcminute scales probed by the ATCA and VLA anisotropy searches. To model this, we assume that each source samples the underlying dark matter density, but has a spatial profile described by a Gaussian radial profile, which leads to a smoothing of the matter power spectrum $P(k)_{smooth} = P(k) \exp(-k^2\sigma^2)$, where $\sigma = \text{FWHM}_{smooth}/2.35$. For the CRB sources to be smooth enough on small scales to have rms fluctuations smaller than the ATCA limits requires the sources to be larger than $\sim 2h^{-1}\text{Mpc}$, as shown by the dotted lines in Figure 1.

Shocks from the formation of large scale structure have been suggested as a source of fluctuations in the radio background (Waxman & Loeb 2000), and would be expected to be spatially extended. However, it has been found that the fractional fluctuations expected on degree scales are of order unity (Waxman & Loeb 2000), more than 10 times higher than the degree scale fluctuations in the models discussed above. To sufficiently suppress power on arcminute scales would therefore require sources even larger than a few Mpc. As discussed in Singal et al. (2010), a substantial contribution from diffuse sources may also be limited by the X-ray and γ -ray background.

The calculations in Figure 1 assumed $b = 1$. At

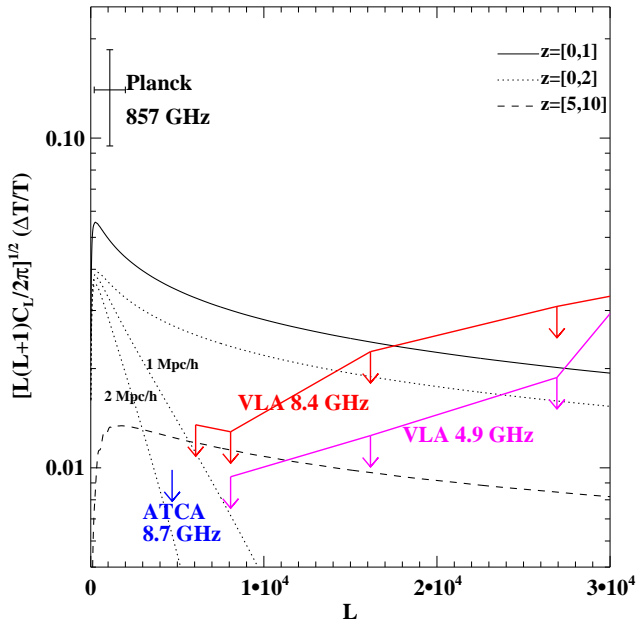


FIG. 1.— Expected clustering for several ranges in redshift for the contributions to the unresolved radio background, as well as the observed upper limits on clustering (using the background temperature T_{excess}). For reference, the amplitude inferred for the cosmic infrared background measured by Planck is also shown. For the redshift interval $z = 0 - 2$ (dotted), the effect of each source being extended is shown: top to bottom are $\text{FWHM}_{\text{smooth}} = 0, 1, 2, h^{-1} \text{ comoving Mpc}$

$z = 0$, a galaxy with $b = 1$ would have a mass near $3 \times 10^{12} h^{-1} M_{\odot}$, while at $z = 5$ this mass corresponds to a mass below $10^6 M_{\odot}$. If the typical contribution is coming from higher masses, the bias factor will be larger, increasing the amplitude of these curves, while to decrease them by the maximum possible factor of ~ 0.5 would require much smaller masses. Even so, reducing the theoretical curves by a factor of two (requiring all the CRB to be generated by dwarf galaxies if it is coming from low z) is still in tension with the ATCA and VLA limits on anisotropy.

4. DISCUSSION

The extragalactic radio background measured by the ARCADE-2 experiment (Fixsen et al. 2011) is remarkably smooth, at a level that makes it unlikely to be generated by emission from a normal population of galaxies. If the sources are cosmological it would be expected that they trace the large scale structure of the universe to some extent. Clustering would therefore generically be expected to be at the level of a few percent for these sources, in conflict with upper limits from deep anisotropy searches on small scales. For comparison, the extragalactic radio background has more than an order of magnitude smaller rms fluctuations than the cosmic infrared background.

It appears that cosmological sources for this background must be either at high redshift ($z \gtrsim 5$), where the clustering amplitude is substantially lower than it is today, or the individual sources must be spatially extended (few Mpc in extent), such that there is not much clustering power on the arcminute scales that have been probed by experiments.

The constraining power of angular clustering measurements is apparent. The upper limits used in this work are all at least a decade old, with the most stringent fluctuation limit being almost 25 years old (Fomalont et al. 1988). With a new generation of radio experiments, it should be possible to greatly improve on these limits. If the clustering amplitude is just below the ATCA/VLA upper limits, this will be easily measured by an experiment such as the Low Frequency Array (LOFAR). At the upper end of their frequency range (240 MHz), the excess temperature would be $\sim 40\text{K}$. If this is clustered at even the 0.5% level, this would produce rms noise fluctuations $\sim 0.2\text{K}$. The typical noise expected for a 1hr observation in the “Core” configuration is expected to be 0.5mJy in a $\sim 2'$ synthesized beam¹, corresponding to a temperature noise per pixel of roughly 0.8K. The clustering would thus be a non-negligible fraction of the noise budget for a typical observation, and could be easily detected in a dedicated power spectrum measurement with just a few hours of observation.

If the excess is not caused by a cosmological population, a possibility is that it is coming from our Galaxy. The radio Galaxy has structure on very large scales; at 2.3 GHz, the power spectrum of the Galaxy on large scales has been found to be roughly $C_{\ell} \sim 0.09 \text{ K}^2 \ell^{-2.9}$ (Giardino et al. 2001) for $\ell \lesssim 100$. Extrapolating this to $\ell \sim 4000$ yields a typical fractional rms temperature fluctuation that is 2% of the excess temperature, again well above the ATCA and VLA limits. Therefore, even if the ARCADE-2 measurements are contaminated by the Galaxy this excess is surprisingly smooth on arcminute scales, requiring the angular power spectrum to be much steeper than ℓ^{-3} on smaller scales.

In summary, the high extragalactic temperature measured by the ARCADE-2 experiment presents a genuine puzzle. Not only is the mean temperature higher than expected based on extrapolations of source counts, but the small-scale fluctuations in this background are much smaller than expected, an order of magnitude smaller than the fluctuations in the cosmic infrared background. Measurements of these fluctuations will be extremely useful for characterizing the source of this background, and the new generation of radio experiments is well-equipped to shed new light on this puzzle.

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¹ www.lofar.org

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